Prospects for Detecting Gamma Rays from Annihilating Dark Matter in Dwarf Galaxies in the Era of DES and LSST

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Among the most stringent constraints on the dark matter annihilation cross section are those derived from observations of dwarf galaxies by the Fermi Gamma-Ray Space Telescope. As current (e.g., Dark Energy Survey, DES) and future (Large Scale Synoptic Telescope, LSST) optical imaging surveys discover more of the Milky Way's ultra-faint satellite galaxies, they may increase Fermi's sensitivity to dark matter annihilations. In this study, we use a semi-analytic model of the Milky Way's satellite population to predict the characteristics of the dwarfs likely to be discovered by DES and LSST, and project how these discoveries will impact Fermi's sensitivity to dark matter. While we find that modest improvements are likely, the dwarf galaxies discovered by DES and LSST are unlikely to increase Fermi's sensitivity by more than a factor of ~ 2. However, this outlook may be conservative, given that our model underpredicts the number of ultra-faint galaxies with large potential annihilation signals actually discovered in the Sloan Digital Sky Survey. Our simulation-based approach focusing on the Milky Way satellite population demographics complements existing empirically-based estimates.

I. INTRODUCTION

Weakly interacting massive particles (WIMPs) are a leading class of candidates for the dark matter of our universe. In many models, the pair-annihilation of WIMPs can produce potentially observable fluxes of energetic particles, including gamma rays. In recent years, observations of the Milky Way's dwarf spherical galaxies by the Fermi Gamma-Ray Space Telescope [1, 2] (as well as by ground based gamma-ray telescopes [3–7]) have yielded constraints on the dark matter annihilation cross section that are among the strongest produced to date, comparable to those derived from observations of the Galactic Center [8] and from searches for dark matter subhalos [9]. For dark matter particles that are lighter than a few tens of GeV and annihilate to quarks, these upper limits are near the canonical cross section predicted for the simplest thermal relics, $\langle \sigma v \rangle \sim 3 \times 10^{-26} \, \mathrm{cm}^3 \, \mathrm{s}^{-1}$.

Dwarf galaxies are promising targets for indirect dark matter searches due to their relatively high densities of dark matter and low levels of astrophysical backgrounds [10–16]. At present, such searches are limited to the 12 dwarfs discovered in the northern hemisphere by the Sloan Digital Sky Survey (SDSS), as well as the 8 previously known classical dwarfs. Future discoveries of additional dwarf galaxies could improve Fermi's sensitivity to dark matter, and possibly to a significant degree. In particular, we expect the currently operating Dark Energy Survey (DES) [17] and the future Large Synoptic Survey Telescope (LSST) [18] (scheduled for 2022), both imaging southern skies, to roughly double the catalog of known satellite galaxies of the Milky Way. In this study, we forecast the characteristics of the dwarf galax-

ies within the reach of DES and LSST, and estimate to what degree Fermi's sensitivity to dark matter is likely to increase as a result of these forthcoming discoveries.

Our focus is on the demographics of the satellite population, and on the importance of which *particular* new dwarfs are found, rather than on precisely quantifying the instrumental sensitivities of Fermi and upcoming optical surveys. See Ref. [19] for a more empirically-based forecast emphasizing Fermi analysis methods and assuming that newly discovered satellites have the same distribution of J-factors (defined in Section II) as those discovered by SDSS.

II. MODELING THE SATELLITE GALAXIES OF THE MILKY WAY

To model the population of dwarf galaxies within the halo of a Milky Way-like galaxy, we have used the results of Ref. [20], which employed semi-analytic techniques to describe the baryonic physics (including ionization, heating, and cooling of gas, as well as star formation and evolution) relevant to the development of satellite galaxies in the largest subhalos of the Aquarius simulation. Drawing from this distribution of 505 simulated dwarf galaxy masses and luminosities (kindly provided to us by the authors of Ref. [20]), and adopting a spatial distribution of satellite galaxies as derived from the Via Lactea simulation [21], we created a large number (approximately 3000) of realizations of a Milky Way-like system.

To determine whether a satellite galaxy is detectable in a given realization, we apply the following criteria. First, we consider any satellite brighter than $M_v = -8.9$ (equal
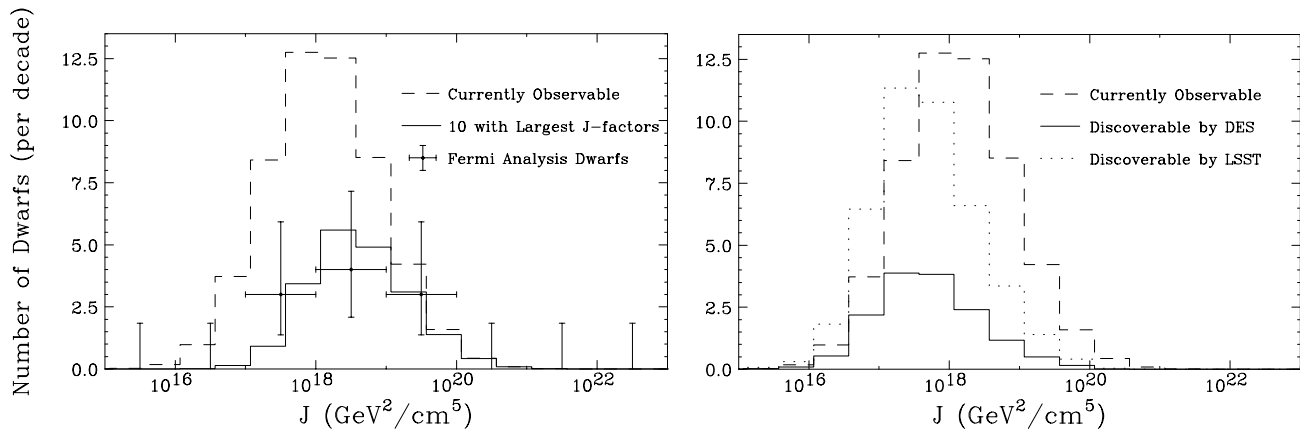
FIG. 1: Left frame: The distribution of J-factors (see Eq. 2) in our model of all currently observable (pre-DES) dwarf galaxies, averaged over approximately 3000 realizations (dashed), and that of the 10 currently observable dwarfs with the largest J-factors, per realization (solid). For comparison, we show the distribution of the J-factors (with Poisson error bars) of the 10 dwarf galaxies used by the Fermi collaboration in their search for dark matter annihilation products [1]. Right frame: The distribution of J-factors of the dwarf galaxies projected to be discovered by DES (solid) and LSST (dotted). Although the average J-factor of DES-discovered dwarfs is expected to be lower than in the currently observable sample (dashed), the tail of this distribution to large J-factors is potentially important, and could lead to improvements in Fermi's sensitivity to dark matter annihilations.

to that of the faintest dwarf discovered prior to SDSS) and well outside of the Galactic Plane ($|b| > 20°$) to be a "classical" dwarf, discovered prior to recent surveys.[1] For a dwarf to have been detected by SDSS, we require that it resides within the region of the sky covered by the survey, and meet the criteria described in Ref. [24]. Based on the relative thresholds for SDSS [25, 26] and DES [17, 27], we adopt a detection criteria for DES which is more sensitive than SDSS by 1.9 in absolute V-band magnitude. Similarly, we adopt a improvement of 5.3 magnitudes in sensitivity for LSST [18]. Due to the challenges involved in identifying dwarfs with a large angular extent, we do not consider any dwarfs located within 10 kpc of the Solar System. To normalize the total number of satellite galaxies in the halo of the Milky Way, we require in each realization that 12 such systems be discoverable by SDSS (not including previously discovered classical dwarfs). On average, we predict that DES and LSST will discover approximately 7.4 and 21.3 previously unknown dwarf galaxies, respectively.

The flux of gamma rays from dark matter annihilations in a given dwarf galaxy is given by:

$$\Phi \equiv \frac{\langle \sigma v \rangle N_\gamma J}{8\pi m_{\mathrm{DM}}^2}, \qquad (1)$$

where m_{DM} is the mass of dark matter particle, N_γ is the number of gamma rays produced per annihilation (which depends on the mass and annihilation channels of the dark matter particle), and the quantity J encompasses the distribution of dark matter within the dwarf:

$$J \equiv \int_{\Delta\Omega} \int_{l.o.s.} [\rho(l, \psi)]^2 \, dl \, d\Omega, \qquad (2)$$

where ρ is the dark matter density and the integral is performed along the line-of-sight. For the solid angle, $\Delta\Omega$, we consider a cone of radius $0.5°$. For the dark matter distribution, we assume an NFW profile [28, 29] with concentrations as prescribed in Ref. [30].[2] We further take each satellite halo to be tidally stripped beyond a radius determined by the Jacobi limit [35].

In Fig. 1, we plot the distribution of dwarf galaxy J-factors produced by our model, averaged over approximately 3000 realizations. In the left frame, we show both the distribution of all currently detectable dwarfs (classical or detectable by SDSS), and the distribution of the 10 currently detectable dwarfs with the largest J-factors, and compare this to those of the 10 dwarfs used by the Fermi collaboration in their search for dark matter annihilation products [1]. From this comparison, we see that our simulation-based distribution is in good agreement with the distribution of actual dwarfs studied by Fermi. However, if we consider only the ultra-faint

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[1] This definition expressed in terms of optical luminosity, though somewhat arbitrary, cleanly partitions the pre-SDSS and SDSS-discovered Milky Way satellites. For comparison, the authors of [22] estimated a completeness threshold of $M_v = -8.8$ to a distance of 180 kpc based on their systematic search through COSMOS/UKST survey data at Galactic latitudes $b < -15°$. See Ref. [23] for a review of optical detection limits prior to SDSS.

[2] Although it has been argued that at least some dwarf spheroidal galaxies may possess dark matter profiles that are shallower than NFW [31–33] (see, however, Sec. 4.4 of Ref. [34]), the J-factors of such systems are expected to be only modestly impacted by the innermost densities (for example, see discussion in Ref. [1]).

dwarfs ($M_\mathrm{v} > -8.9$), we find that our model underpredicts the actual number of dwarfs with large J-factors detected by SDSS. It is therefore likely that our model provides a conservative estimate for the discovery potential of DES and LSST. We discuss this point further in Section IV.

In the right frame of Fig. 1, we show the distributions of dwarfs predicted to be discovered by DES and LSST according to our model. The populations predicted to be discovered by DES and LSST exhibit somewhat smaller average J-factors in part due to the ability of these surveys to detect dwarf galaxies at larger distances.

III. STATISTICAL APPROACH AND PROJECTIONS

It is possible to estimate how the discovery of additional dwarf galaxies will improve on Fermi's sensitivity to dark matter in a way that is largely independent of the details of the gamma-ray spectrum and Fermi's instrumental response. In the gaussian limit (applicable for gamma-rays from a large number of dwarfs, at energies at a few tens of GeV or below), we can write:

$$\chi^2 = \frac{(\mathrm{Observed} - \mathrm{Background})^2}{(\sqrt{\mathrm{Background}})^2}, \qquad (3)$$

where the above quantities denote the total observed dark matter annihilation signal-plus-background and the total background summed over the combination of the regions surrounding the dwarfs used in a given analysis. To derive the 95% upper limit on the annihilation cross section, we set $\chi^2 = 3.84$. Combining this with Eq. 1, we obtain:

$$\langle \sigma v \rangle \lesssim \frac{8\pi m_\mathrm{DM}^2 (3.84 \sum_i B_i)^{1/2}}{A_\mathrm{eff}\, t^{1/2}\, N_\gamma \left(\sum_i J_i\right)}, \qquad (4)$$

where A_eff is the effective area of Fermi, t is the duration of the observation, and B_i is the rate of background events in the direction of dwarf, i.[3]

If DES (or LSST) discovers any dwarf galaxies with large J-factors, Fermi's sensitivity to dark matter annihilation will be strengthened. In particular, making use of $(N-10)$ new dwarf galaxies discovered by DES or LSST, Fermi's sensitivity to the dark matter annihilation cross section is predicted to improve by a factor given by:

$$\frac{\langle \sigma v \rangle_\mathrm{old}}{\langle \sigma v \rangle_\mathrm{new}} \simeq \sqrt{\frac{t_\mathrm{new}}{t_\mathrm{old}}} \left[\frac{\sum_{i=1}^{N} J_i}{(\sum_{i=1}^{N} B_i)^{1/2}} \right] \left[\frac{\sum_{i=1}^{10} J_i}{(\sum_{i=1}^{10} B_i)^{1/2}} \right]^{-1}$$

$$(5)$$

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[3] Although we characterize the background for each galaxy using a simple Galactic latitude-dependent model based on data from Fermi, in practice the background can be estimated using more sophisticated diffuse models, or by directly studying the gamma-ray emission observed from the region surrounding the dwarf in question.

Note that in performing this summation, we include only those newly discovered dwarfs with large enough J-factors to improve upon the limit. Dwarfs with lesser J-factors and/or with large expected backgrounds that would diminish the overall sensitivity are not utilized. By scaling this estimated sensitivity to that already presented by the Fermi LAT Collaboration, we can present our results in a form that is approximately independent of quantities such as the particular choice of the dark matter annihilation channel and Fermi's effective area, instead depending only the observation time, and on the J-factors and latitudes of the dwarfs to be discovered by DES and/or LSST.

Our counts stacking approach represents a considerable simplification relative to the joint likelihood analysis employed by the Fermi LAT Collaboration, which would be beyond the scope of this study to implement. However, our method still incorporates information regarding the distribution of J-factors among detected dwarfs by selecting the combination of dwarfs in each realization which would yield the highest *a priori* signal-to-noise ratio according to Eq. 5. The χ^2 treatment presented here has greatest fidelity in the high-counts (i.e., background-dominated regime) relevant for dark matter masses of $\lesssim 300$-500 GeV. For larger masses, a Poisson treatment should be used.

For simplicity, we assume the uncertainties in the relevant J-factors to be negligible (after spectroscopic follow-up). While this is not likely to be entirely realized, as we treat both currently known dwarfs and to-be-discovered dwarfs in this way, this assumption is unlikely to significantly impact our projections for the *improvement* in Fermi's sensitivity.

In most cases, we find that Fermi's sensitivity to dark matter annihilations in dwarf galaxies is largely determined by the dwarf with the largest J-factor. Among the 10 dwarfs currently used in the analysis of the Fermi LAT Collaboration, it is the combination of five dwarfs with the largest J-factors (Ursa Major II, Draco, Ursa Minor, Coma Berenices, and Segue 1, each of which with $J \approx 0.3 - 4.0 \times 10^{19}$ GeV^2 cm^{-5}) that dominate the calculation of the resulting limit. Any future discoveries of dwarfs with J-factors below a few times 10^{19} GeV^2 cm^{-5} are unlikely to impact this limit significantly. Instead, in most of the realizations in which Fermi's sensitivity improves significantly as the result of the discovery of new dwarfs, it is a single dwarf with an exceptionally large J-factor that accounts for the vast majority of the improvement. In other words, significant improvements in Fermi's sensitivity to dark matter are possible, but generally rely on the discovery of a nearby satellite, containing too few stars to have been previously identified as a classical dwarf.

With this in mind, we show in the left frame of Fig. 2 the probability of DES or LSST discovering at least one dwarf with a J-factor above a given value. From this, we see that there is approximately a 5.1% (13.6%) chance that DES (LSST) will discover a dwarf with a larger J-
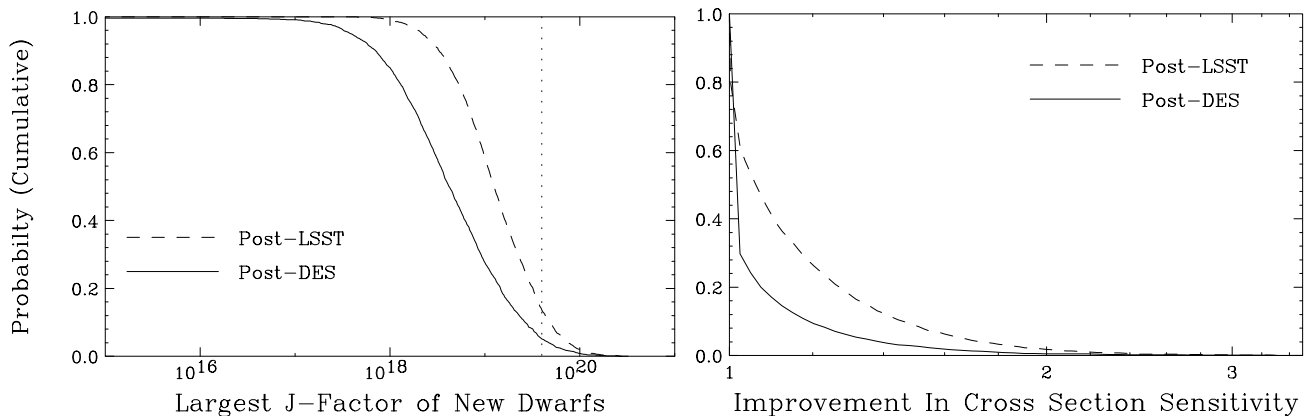
FIG. 2: Left frame: The estimated probability that DES or LSST will discover a dwarf galaxy with a J-factor greater than a given value. The vertical dotted line denotes the largest J-factor of the currently known dwarfs ($10^{19.6}$ GeV^2 cm^{-5}). Right frame: The estimated probability that new discoveries by DES or LSST will enable Fermi's sensitivity to dark matter annihilations to improve by a given value. Note that the improvement shown here does *not* account for increased exposure, but only the inclusion of newly discovered dwarf galaxies.

factor than any of the currently known satellites. In the right frame, instead of focusing on the single dwarf with the largest J-factor, we show the estimated likelihood of Fermi's sensitivity to dark matter annihilations improving by a given factor. Note that the improvement shown here does *not* account for increased exposure, but only to the inclusion of newly discovered dwarf galaxies.

IV. DISCUSSION

To those hoping that the new dwarf galaxies to-be-discovered by DES or LSST are likely to significantly improve Fermi's sensitivity to annihilating dark matter, the results presented in the previous section may be disappointing. In this section, we briefly discuss the most important assumptions that have gone into our model, and consider how other approaches could potentially lead to more optimistic projections.

First of all, we reiterate that our model is based on the mass-luminosity distribution of dwarf galaxies presented in Ref. [20], spatially distributed according to Ref. [21], and normalized such that SDSS discovers 12 previously undetected dwarfs. While we consider these choices to be reasonable, it is possible that they lead to a population model of satellite galaxies that does not precisely correspond to that of the Milky Way. In particular, we note that while our model predicts that the currently observable satellites with the highest J-factors are likely to be classical dwarfs, rather than those discovered by SDSS. In reality, however, the two known dwarfs with estimated J-factors larger than 10^{19} GeV^2 cm^{-5} (Segue 1 and Ursa Major II) were both discovered by SDSS (Coma Berenices, also discovered with SDSS, has a J-factor near this threshold, $J \simeq 10^{19}$ GeV^2 cm^{-5}). The predicted probability of SDSS discovering two dwarfs with $J > 10^{19}$ GeV^2 cm^{-5} is approximately 12.5%. So while such a re-

alization is not wildly unlikely, it may be indicative that our model underestimates the number of ultra-faint satellites with large J-factors.

As an alternative approach to that adopted in our model, we could have normalized each simulated system such that SDSS would have been able to discover two or three dwarfs with $J > 10^{19}$ GeV^2 cm^{-5}. This would increase the number of high J-factor dwarfs predicted to be discovered by DES and LSST by a not insignificant factor of ~4-6. Had we instead normalized according to the number of SDSS-discovered dwarfs with $J > 10^{19.5}$ GeV^2 cm^{-5}, the normalization would increase by a factor ~ 15 on average.

According to our model, a fundamental limitation to future sensitivity gains is that ultra-faint dwarfs ($M_v > -8.9$) with J-factors similar to or larger than any of the currently known dwarfs are rare, and ultra-faint dwarfs with $J > 10^{20.}$ GeV^2 cm^{-5} are almost non-existant. However, the tail of high J-factor ultra-faint galaxies might be more prominent in reality than accounted for in our model, based on the discussion above. Of course, it is also possible that the SDSS footprint contains a fortuitously large number of high J-factor ultra-faint satellites. Estimation techniques that treat the SDSS sample as perfectly representative are necessarily blind to this possibility, which motivates simulation-based methods as an important complementary approach.

Our conclusions intrinsically, and not insignificantly, depend on the luminosity function of dwarf galaxies, which is not currently well constrained observationally at the faintest luminosities [36]. To illustrate this dependence, we show in Fig. 3 the distances and V-band magnitudes for a random sample of dwarfs with J-factors larger than $10^{19.6}$ GeV^2 cm^{-5} (the largest value of the currently known dwarfs), as predicted in our model. This figure illustrates two key features. Firstly, all dwarfs with such large J-factors are located relatively nearby, within
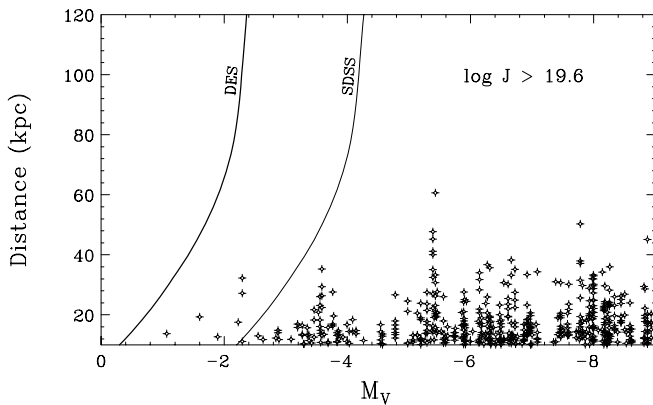
FIG. 3: The distance to and V-band absolute magnitudes of a random sample of dwarf galaxies in our model with J-factors larger than $10^{19.6}$ GeV^2 cm^{-5}. Also shown are the approximate thresholds for SDSS or DES to detect a given dwarf galaxy. Note that in our model, all dwarfs with such larger J-factors are relatively nearby, and few (none) are too faint to be detected by SDSS (DES).

~ 60 kpc of the Solar System. And secondly, very few of such dwarfs are too faint to have been detected by SDSS, and none will be missed by DES or LSST (if within their fields-of-view). If we had instead considered a model with a luminosity function predicting a much larger number of dwarfs with magnitudes fainter than $M_V \sim -3$, the prospects for DES and LSST could be improved. The model proposed in Ref. [21], for example, predicts a sharp increase in the number of dwarfs fainter than $M_V \sim -4$, leading one to expect more discoveries of high J-factor dwarfs by DES and LSST than is predicted in the model we have used in this study, and thus to more favorable predictions for the future sensitivity of Fermi to annihilating dark matter.

V. SUMMARY

Using the semi-analytic model of Ref. [20] (and the spatial distribution of Ref. [21]), we have created a large sample of the satellite populations around Milky Way-like galaxies, and have used these results to project how future discoveries of dwarf galaxies by DES and LSST are likely to impact the sensitivity of the Fermi Gamma-Ray Space Telescope to annihilating dark matter. We find that the expectations for such improvements are modest, with little chance that future surveys will increase Fermi's sensitivity to dark matter by more than a factor of ~ 2. From this perspective, the prospects for improving Fermi's sensitivity to dark matter annihilating in dwarf galaxies largely rely on continued observation (*i.e.* greater exposure) and from tightening the dynamical constraints on the currently known dwarfs because the "best" targets would probably have already been found.

We caution that these conclusions are based on one set of modeling choices for the Milky Way satellite population and that more optimistic forecasts based on different approaches are possible. In particular, the mock satellite populations considered here may be deficient in ultra-faint galaxies with high J-factors, which in reality substantially strengthen the current limits derived from Fermi observations. Further investigations into the luminosity function, radial distribution, and dark matter halos of the faintest Milky Way companions are needed to more precisely predict how much DES and LSST will help to improve dark matter annihilation constraints.

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